Data Compression for Space Missions

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Summary

For many space missions, the ability of spacecraft sensors to acquire meaningful data may surpass to a considerable extent the ability of the telemetry system to transmit this data to earth. It is often possible, however, to receive at the Earth a large portion of the sensed data by preprocessing or compressing the data before transmission in order to remove redundancy or useless information. This paper discusses data compression as applied to space missions. Since the usefulness and form of data compression is dependent to some extent on the particular space mission under consideration, certain general classifications of space missions are considered in light of their amenability to data compression. Some basic compression techniques are applied to example sets of data, and the results show that a rather small increase in onboard data processing can result in a severalfold increase in the amount of data transmitted to Earth. The compression procedures used are limited to those easily implemented by the unsophisticated but highly reliable data processing equipment likely to be present on future spacecraft. Curves are developed showing the compression ratio of various techniques as a function of allowable approximation error and complexity of mechanization. Data compression relationships as functions of reliability are also presented, where reliability is related to the loss of data per bit error in transmission. This analysis shows that certain tradeoffs exist since, in general, higher compression ratios are obtained at the expense of less accurate data representation, more complex implementation, and higher loss of data per bit error in transmission.

Introduction

Although data compression is potentially useful in many areas, for space missions its primary role is to reduce or compress the amount of raw data obtained from various sensors in order to reduce the requirements of the telemetry system. That is, lower amounts and rates of data permit use of smaller transmitting antennas, power supplies, receiving antennas, etc. There are many techniques that can qualify as "data compressors" such as analog-to-digital converters using a finite number of bits for digital signal representation, or an astronaut who deletes information he regards as useless.

After a brief review of general types of space missions, this paper considers several basic types of compression techniques and develops relationships useful for a tradeoff analysis of the procedures. Raw sensor data obtained from the Mariner 4 mission to Mars in 1964-65 is used as an example of spacecraft data. Relationships are developed for the effect bit errors in transmission have on the decoded data, and procedures are presented for limiting the effect of such errors.

Space Mission Data Characteristics

In a March, 1965 compilation of satellite and spacecraft programs[1], there were 47 entries. This did not include some known classified programs. Rather than considering data compression for each of these programs, three general categories of space missions are discussed. These three types of missions are: 1) interplanetary, 2) lunar, and 3) near Earth. Manned missions, because of their complexity and the intractableness of describing the role man plays in the data compaction process, were considered beyond the scope of this paper and are given only passing consideration.

Interplanetary Missions

The Voyager and Mariner Programs represent the primary planned interplanetary exploration effort for the next decade. Communication characteristics of the Mariner Mars 1964 mission indicate a requirement for data compression, because during encounter, video data was obtained at a rate of 10,700 bits per second (bps), but the transmission rate to Earth stations was limited to 8-1/3 bps[2]. Video data waiting for transmission was stored on an endless loop tape. This process of recording data at a high rate in order to transmit at a slower rate appears to be a part of the Voyager mission as well, because video and other data will probably be acquired during a small portion of the spacecraft's orbit of the planet, while the majority of the orbital period will be used to transmit the data to Earth.

Projections of the state-of-the-art of interplanetary and lunar communication systems[3] show an increasing ability to transmit information at interplanetary distances. While these projections indicate considerably increased communication capability, the spacecraft payloads will also be increased, and it is natural to expect a much larger amount of data will be gathered by television receivers and other sensors mounted on orbiting, landing, and ground roving equipment. The increased communication capability is based on use of new, large (210-foot diameter) receiving antennas. It is difficult to conceive of much larger rotating antennas, but one can envision much larger payloads than the 600-pound Mariner and 10,000-pound Voyager spacecraft. Because of the long distances between planets like Earth and Mars (or even worse, Jupiter or more remote planets), the communication link would always appear to be critical. When considering transmission of data across such large

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distances, it would seem that data compression methods could permit significantly increased communication efficiency in terms of useful data transmitted.

Lunar Missions

The Ranger, Surveyor, Lunar Orbiter, and Apollo projects are the planned programs for the exploration of the moon. The Ranger spacecraft and mission differs from the Mariner interplanetary mission in that data transmission is analog and in real time rather than digital from a stored media.[4] The transmission of information from the moon is not so difficult either, because it has been shown that the transmitter power required for a lunar mission utilizing a properly designed PM (phase-modulated) system is 12.5 mv for a 5 cps bandwidth and 10.7 watts for voice communications.[5] The large DSIF antennas must be used, however.

It would appear that use of data compaction in immediate lunar missions is somewhat marginal because of the existing communication capability and the limited number of launches planned. For advanced missions, however, where a number of sources may be transmitting information simultaneously such as from long life or semipermanent stations established by Surveyor, Lunar Orbiter, or Apollo missions, data compression could well be used to send only useful information and not saturate the receiving stations with redundant or useless data. Other constraints argue in favor of data compressions because, for the Surveyor Mission, television surveys consisting of many frames must be interrupted for up to 2-hour periods near the lunar noon for thermal cooldown of the compartments in accordance with thermal constraints.[6] Because the amount of data from a typical lunar photographic mission will saturate a battery of observers, pattern recognition techniques performed by a digital computer are proposed to automatically reduce the data.[7] The computer will be asked to recognize the various lunar features and to categorize them according to the relation of certain features to their neighbors, the number of such features, and their description. It is conceivable that such data reduction or similar compression could be performed onboard the spacecraft and only the results transmitted. For certain types of experiments, the transducers themselves could perform the data reduction.[8]

Near-Earth Missions

Of the 47 entries in reference 1, over 37 describe near-Earth missions. To facilitate the discussion of data compression applicable to each, these missions have been somewhat arbitrarily divided into the five following categories: 1) communications, 2) test and measurement, 3) surveillance, 4) detection, and 5) manned missions.

Communication Satellites. Satellites such as Echo, which are passive, and those of the Comsat Corporation, which may be active repeaters, function primarily as a relay of messages. Although some data compression could conceivably be done by satellite equipment on the incoming messages, a better place in most cases would be the ground transmitting station where the data originate. For this reason, communication satellites do not appear to be fruitful areas for the application of onboard data compression and are not considered further.

Test and Measurement Satellites. Satellites falling into this category would be BIOS, a satellite to test effects of space environments on plants, animals (primates), and other biological specimens; PEGASUS, a meteoroid detection satellite; GEOS, a geodetic satellite to carry flashing-light beacons, electronic beacons, and optical and radar reflectors; and OGO, a satellite with instruments for geophysical measurements. Onboard data compression would be useful to transmit only certain parameters of the experiment such as the mean and variance and perhaps some information describing the probability distribution of certain random processes such as meteorite impacts. A characteristic of this category is that relative long-time intervals are required for obtaining data (i.e., number of meteorite impacts or effect of space environment on plant life) as contrasted with the rate at which the Ranger vehicle obtained video data in the few minutes before impact. Hence, it would appear that the addition of separate data compression hardware might not be too profitable, as the data acquisition rate is probably fairly well matched to the available transmission rate.

Surveillance Satellites. Typical of this category are the TIROS and NIMBUS weather satellites. A variety of TV and radiometer[9, 10] sensors are employed to ascertain cloud cover characteristics and to gather heat balance data. The primary mission of these programs is the gathering of data, and with television employed as the sensor, large amounts are obtained. For NIMBUS, video data is acquired at the rate of approximately 5×10^6 bits per second in order to give coverage over the entire daytime portion of the orbit. Such large amounts of data and required processing equipment naturally suggest data compression techniques. The transmission problem is further compounded when only a limited number of ground receiving stations is used. Data gathered over a large portion of the orbit must be stored for rapid transmission when the satellite is in contact with one of these ground stations, causing the need for high transmission rates.

Detection Missions. The MIDAS and other programs of the Air Force are representative of this class wherein IR sensors are used to detect ICBM launchings. Another member of this class are the Nuclear Detection Satellites (formerly VELA) for the detection of nuclear explosions in space. Characteristic of this category is the need for surveillance of large areas by a number of sensors, but where the sensors output is of little interest unless a particular event occurs. Continuous transmission of the output of each sensor could result in extremely large amounts of data, most of which contain little information, except that a particular event has not occurred. Because, under prevailing conditions, there are few times when the output of the IR sensors is above a certain threshold, it would appear desirable to transmit information from a sensor only when its output is significantly different from the expected level. For these reasons, this type of mission seems particularly amenable to data compression.

Manned Missions. Man is often a good compactor of data, because he can discern and report new, unusual, or unexpected events. Manned missions invariably have extensive communication capability because of the concern for the astronauts condition. Also, because it is planned to recover physically at least a portion (the manned portion) of all space vehicles involving astronauts, data accumulated during a mission can be received on the Earth via photographs, tape recordings, etc., taken from the returning vehicle. Because of these conditions, data compression hardware may not be as essential in manned missions as in some other space missions. On the other hand, there may well be a need for receipt of large amounts of video and other data during the mission for control or monitoring purposes. Here data compression techniques might profitably be employed to report only abnormal conditions such as unusual electrocardiograph activity.

This section has attempted to define in a brief and general way certain space missions in light of their need for data compression. The missions that appear to hold the most promise for the application of such techniques are interplanetary, near-Earth surveillance and near-Earth detection.

Compression Techniques

To a large extent, the type of compression scheme used in a mission is a function of the mission requirements. Consequently, the various data compression techniques have been somewhat arbitrarily grouped into five categories according to requirements placed on the transmitted data. These categories are:

1. Information Preserving Compression. Here data is to be transmitted so that no errors are introduced and all information is retained.

2. Minimum Error Compression. In this category, some specified error can be tolerated in the transmitted data, but information concerning each data point must be received. That is, for transmission of TV images, information on each quantized interval of all scan lines is to be sent, but the magnitude of the brightness can have some error such as that due to digital quantization or approximation.

3. Removal of Nonsignificant Data. Here most of the sensed data is not of interest such as in the MIDAS ICBM launch detection system where the IR sensor output is usually below some threshold level and thus only of interest in indicating that no launches have occurred.

4. Determination of Statistical Properties. Often only the statistical nature of certain measurement data is of interest as in determination of ion density or distribution of meteorite impacts. The data compression in this case results in the determination of certain statistical parameters such as the mean or variance of certain points on a probability distribution curve.

5. Complete Data Reduction. Certain space missions can have certain specific objectives such as determining the location of certain enemy defenses by satellite reconnaissance. Conceivably, the data sensed by the satellite sensors could be reduced onboard to the point where only the type and geographic location of enemy forces need be transmitted.

The remainder of this section discusses various data compression techniques as they are related to these five categories. As can be surmised from scanning the rather lengthy but incomplete list of references at the end of the paper, a complete description of each proposed technique is beyond the scope and intent of this survey. Certain generalizations are made (as in the preceding categorization) and various specific proposals treated as modifications and refinements of basic procedures.

Information Preserving Compression

A certain amount of errorless data compression can be obtained for digitized or quantized data by use of optimal coding techniques[11, 12, 13]. Optimal coding uses known or assumed statistics for the expected sensor data in order to assign the shorter codes to the more probabilistically likely data values[14]. Shannon-Fano[15] and Huffman[16] codes are the basic codes used in such procedures. A number of investigations have been conducted to determine the statistics of various types of data such as TV images[17, 18, 19, 20, 21] and even languages[22, 23]. Application of information theory, notably the calculation of the entropy of the data source, has enabled calculation of the maximum compression that can be obtained using optimal coding[24].

For digital data, run length coding has been extensively studied[25, 26]. With this technique, a new measurement value is transmitted only if it is different from the previous value. Timing information must also be conveyed such as the number of seconds a measurement assumed a certain value. Optimal coding can be applied to the data values and run lengths to aid in the reduction.

Investigations have shown it is often advantageous to transmit only the difference between successive data values and use run length coding for such differences[17, 20, 26, 27]. A savings is often achieved because small differences are more likely and thus more suited to optimal coding than straightforward coding of each absolute value. The compression that can be achieved is obviously largely a function of the data. Video images of a portion of the lunar surface, with very few craters and rather uniform surface brightness, can be compressed much more than a checkerboard image where the checkerboard squares are of the same size as the resolution elements. For somewhat typical aerial photographs of varied terrain, compression ratios of 2 - 3 are representative.

Minimum Error Compression

Because in this category a certain amount of error is permissible, a variety of approximation techniques may be employed, each keeping the error in the transmitted data to some specified minimum. Run length coding and variations of it called floating aperture[28, 29, 30, 31, 32] zero-order polynomial prediction, first-order polynomial prediction, zero-order polynomial interpolation and first-order polynomial interpolation have been developed and extensively studied[33, 34, 35, 36, 37]. The basic idea in these techniques is to transmit a new data value only if it varies from a predicted value by more than some specified amount.

The term "floating aperture" refers to the "opening" through which each succeeding data value must fit if it is not to be transmitted. Various studies have been performed with variable or adaptive aperture[38, 39, 40] particularly as a function of the loading in buffers holding data to be transmitted.[41]

The zero-order polynomial prediction schemes, ZOPP, uses the data points at sample time T-1 to predict the data point at sample time t. If the error in the prediction is less than some specified amount, no new value is transmitted. The first-order polynominal prediction scheme, FOPP, is similar and uses the data values at t-1 and t-2 to predict the value at t. Higher order prediction schemes have been investigated[42] but not found to be too useful because less and less significance is attached in an unweighted system to the most recent data values.

In the zero-order polynomial interpolator algorithm, ZOPI, the tolerance is placed about the first sample; but instead of the tolerance remaining fixed, the upper and lower bounds are modified by subsequent samples so that the first out-of-tolerance sample will cause a value to be transmitted that will approximate the arithmetic mean of all samples between this value and the previous transmission. Following each transmission, the original programmed tolerance is reestablished about the current sample value and the process is repeated. Thus, the compressed data transmission consists of a series of interpolated mean data values.[43]

The first-order polynomial interpolator algorithm, FOPI, is similar to the zero-order interpolator algorithm, except that interpolations are made with respect to slope. That is, mean slope of data samples over the time interval are presented, and no data value during this time will differ from this straight line by more than the specified tolerance.

A number of other approximation schemes exist. Data points can be approximated by a sum of orthogonal polynomials[44] using a minimum mean square error criteria rather than a maximum error criteria in the approximation. For certain types of quasi-periodic data such as EKG (electrocardiagram) waveforms, cycle-to-cycle redundancy reduction has been reported[45] with compression ratios up to 1800:1. More complex hardware is often required for such reduction, however. Techniques for the improvement and refinement of TV images by certain operations on the bits describing the gray levels have been studied.[46,47]

With all of these compression schemes, the amount of compaction attainable is highly dependent on the data and the approximation error that can be tolerated. Compression ratios ranging from 2:1 to 100:1 or higher have been reported for various data. Many studies and simulations have used actual data obtained from various space missions in order to more accurately assess the performance of a proposed compression technique.[19,20,45,43,48,49,50,51] Some of these techniques have been mechanized with hardware configurations suitable for airborne and space environments.[38,52,53] Effort has also been spent studying and simulating the size of buffers and the effect of buffer overflow in those compaction schemes requiring buffering of information awating transmission.[54]

Removal of Nonsignificant Data

In many space missions and experiments, sensors may be designed and oriented to detect special events such as meteorite impact or ICBM launchings. When the output of the sensor exceeds some threshold, a particular event has occurred and the sensor data may give specific quantitative information concerning the event. For output values less than the threshold, the data is not of real interest except in establishing that a particular event has not occurred.[32,55] If the frequence of occurrence of the special events is low, large compression ratios can be obtained.[56] Development of general compaction techniques that fit this category is difficult because of the strong dependence of an optimal system on particular mission characteristics. One such data compressor of this type has been designed that has many input data sources and uses an addressing scheme to decide which of the inputs are above the threshold.[57] Another event of interest might be the maximum or minimum value of a measurement such as temperature or pressure. For certain missions, compression ratios can be of the order of 700:1.[32]

Determination of Statistical Properties

When only statistical properties of certain measurements are required, rather large compression ratios are possible. In fact, for certain types of experiments, the transducer itself can do some or all of the averaging.[32] For example, average air pressure over a five-minute interval could be measured directly, instead of by computation, withproper instrument design. Other important statistical parameters include variances, correlation, maxima, and minima.

Of the various statistical properties, the spectral density is often one of the most useful; and in a number of cases, such as in vibration signals from missiles and spacecraft, it is the only information that is systematically extracted.[58] Studies leading to the design and development of airborne spectrum analyzers for telemetry bandwidth compression have been performed.[58,59,60] Such equipment not only reduces telemetry requirements, but presents data in a form suitable for immediate use.

Another technique involving averaging and resulting in spectral information involves compression of bio-astronautical data.[61] Moving-average bandpass filters are used to analyze the spectral distribution of the brain-wave activity as measured by an electroencephalograph. Averages are obtained over the five frequency ranges corresponding to the five classifications commonly used in EEG (electroencephalograms) studies. These data, transmitted at intervals, are displayed for the observation of a medical monitor.

It is also possible to achieve a substantial compression ratio for measurements with random characteristics by transmitting information sufficient to describe the probability distribution function of such a process. A number of rather theoretical studies have been performed,[62,63,64,65,66,67] and have been applied to the extent that a mechanization scheme has been developed and an engineering model of a quantizer is being built as a predecessor of a flyable deep space model.[68]

Complete Data Reduction

This category represents the most ambitious of all compression areas in that all data reduction that would be performed on raw data would be done by on-board computers. As such, and considering the state of present and projected space efforts, very little has been done or is likely to be done in the near future as far as implemented systems are concerned. However, systems have been developed for the automatic selection of targets from raw data consisting of radar and infrared signals.[69] Much of the work of feature extraction in pattern recognition work could conceivably be useful in this area. Some work has also been done on the compression of TV images by determining and transmitting "line drawings" of certain objects in the viewing field.[70, 71]

Trade-off Analysis

It is difficult to make comparisons between the various techniques without reference to specific examples. On the other hand, the usefulness of the procedures is dependent on the type of data to be compressed. Certain example sets of data can be fabricated so that any one technique appears better than all others. For example, the zero-order polynomial predictor will be better than all others for data that is constant with time, while the first-order polynomial predictor is best for data that is increasing with time. Assuming some allowable error in the data, the zero-order polynomial interpolator will be best for somewhat constant data with random variations about the nominal while the first-order polynomial interpolator will be best for the same types of data that has a linearly increasing or decreasing bias. For concreteness, however, a specific representative example was chosen for analysis and represents raw magnetometer data taken from a more active period of flight of the Mariner IV spacecraft during the 1964-1965 mission to Mars. (Figure 1 shows this set of data.)

The compression techniques considered are limited to those of class one and two as described in the previous section. These are standard difference coding, optimal coding of differences (Huffman coding), zero- and first-order polynomial predictor (ZOPP, FOPP) with various permissible maximum errors, and zero- and first-order polynomial interpolators (ZOPI, FOPI) also with various permissible maximum errors. Each of these techniques are rather easily and reliably implemented and thus suited for interplanetary missions.

Table 1 gives the results of the compression analysis using each of these techniques. The remainder of this section discusses the manner in which the entries of this table were generated. The curves of Figures 2 and 3 are plots of the data in Table 1.

Direct Coding

Because the magnitude of the example data function varies from -22 to 17, at least 6 bits are required to send each data value. If 220 data points are to be sent, 1320 bits must be transmitted. This number is used as the amount of data that must be sent if no compression techniques are used so that the entry in Table 1 under "compression ratio" is 1. The complexity measure for each technique was obtained by writing a set of typical computer machine language instructions necessary to process the raw data and store the information to be transmitted in a buffer to await transmission. The complexity measure is the average number of these instructions that must be executed for each raw data point. Because for direct coding all data points are to be transmitted, it is assumed only two instructions, a "clear-and-add" and a "store" instruction are necessary. This gives the complexity measure of 2 shown in Table 1. No error is involved in the processing so that the entry in column four for this procedure is zero.

Difference Coding

With this procedure, only the difference between successive data points is transmitted. Since the differences in the data functions can have five values according to Figure 1, three bits are necessary to define each transmitted data point or 660 bits for the entire 220 points. This gives a compression ratio of 2.0. The complexity measure for this procedure is five, and there is no error in the transmitted data.

Huffman or Optimal Coding of Differences

With the statistics for the differences found from Figure 1,

$$H_D = -\sum_{i=1}^{N} P_i \log P_i$$

$$= 1.45 \text{ bits/data point}$$

A Huffman code for the difference D is shown in Table 2. The average number of bits required per data point can be determined from

$$\sum_i N_i P(C_i) = 1.55 \text{ bits/data point}$$

where C_i is the particular code, N_i is the number of bits in the code C_i, and $P(C_i)$ the probability of code C_i occurring. This figure of 1.55 bits/data point leads to a compression ratio of 3.88 as shown in Table 1. The complexity measure was found to be 8.

Zero-Order Polynomial Predictor - (ZOPP)

With the ZOPP, after an initial data value is sent, only differences are transmitted if their magnitude exceeds the specified minimum error denoted by A. Thus, if no value of D is transmitted, the value of y at t is assumed to be the same as at t-1. For optimum channel use, timing information must also be transmitted that indicates at what instant of time the change in y is to occur. Thus, if A = 0, then the data values to be transmitted for the example over the first 12 seconds would be, after the initial value of -22 has been transmitted, (0100) (001) (0001) (101) (0010) (001) (0010) (001) (0001) (101) (0001) (001). The parentheses are used only for clarification and indicate separate blocks of information. Those blocks containing four bits denote the time since the last transmission that the next difference would occur. The blocks containing three bits specify the amount of the change, the first bit indicating the sign. Thus, 7 bits must be transmitted every time a change in y exceeding A occurs.

It is possible to only use 2 bits to code the change in y, because the maximum change is 2 in either a positive or negative direction, and a change of zero is never transmitted. Thus, the eight possible changes in y can be coded using only 2 bits. However, there is a nonzero but very small probability that y has the same value for a large number of time intervals. If this is the case, then the range of the counter indicating how many time-intervals since the last change in y, must have a large capacity. (Theoretically it must use an infinite number of bits to allow for the possibility of an infinite number of consecutive times intervals over which y is the same.) This difficulty can be overcome by permitting a zero change in y to be transmitted if the capacity of the counter is reached. This means, for the example under consideration, that 5 states or changes in y are possible, thus requiring a 3 bit code to specify the change. This permits finite size counters to be used.

When determining a code for the changes in y, it may be desirable to choose a shorter code than necessary to specify the entire range of the changes, as in the case where small changes are more likely. Changes in y that exceed the limit of the code can be handled by transmitting a number of blocks of data with a time interval of zero for each such block except the last. The sum of the changes recorded by each block equals the actual change in y.

Using the 7-bit code described above, examination of the data of Figure 3 reveals that y change 84 times, requiring therefore 588 bits to be transmitted for a compression ratio of 2.24. If a 3-bit counter and a 2-bit code for differences are used, there are 87 transmissions of 5 bits each giving a compression ratio of 3.04. This is greater than 2.24; and therefore, a 3-bit counter and a 2-bit difference code are used. No approximation error is involved, and the complexity is 12.6.

If A is allowed to have increasing values, the other entries of the table under the ZOPP section are obtained. In each case, various sizes of counters and difference codes were examined and those selected that resulted in the highest compression ratio even though the counter and difference capacity may sometimes be exceeded.

Zero-Order Polynomial Interpolator - ZOPI. The entries of Table 1 for the ZOPI were determined in a similar fashion as those for the ZOPP, the only difference being the differences in the techniques themselves. As one would expect, and as shown by the curves of Figures 4 and 5 and the entries of Table 1, the ZOPI provides larger compression ratios but is also more complex to implement.

First-Order Polynomial Predictor (FOPP). With this form of prediction, two data values are used to predict succeeding values. If the prediction is within the error tolerance, no new data is transmitted; new information is transmitted only when examination of successive data points reveals one which does not lie within the predicted region. For the first-order polynomial process, straight lines are involved and the process has the form:

$$y_{t+n} = y_{t+k} + (y_{t+k} - y_{t+k-1})\,N$$

$$I_{t+n} = \begin{cases} 0 \text{ if } \left[\hat{y}_{t+n} - y_{t+n}\right] < A \\ \left[y_{t+n} - \hat{y}_{t+n-1},\ y_{t+n+1} - y_{t+n},\ N\right] \\ \text{otherwise for case B } (FOPP_B) \\ \left[y_{t+n} - y_{t+n-1},\ N\right] \\ \text{otherwise for case A } (FOPP_A) \end{cases}$$

where

$\hat{y}_t$ is the predicted value of y at time t

y_t is the actual value of y at time t

I_t is the information transmitted at time t

N is the number of time intervals $= t+n - (t+k)$

k designates the time interval at which the last transmission of information occurred

A is the magnitude of the permissible maximum error

and where equal time intervals between data points have been assumed. Notice that two different forms of first-order polynomial predictors are involved. These are defined by the foregoing equations. Again counters must be used; and when new information is transmitted, N is used to transmit this information. The difference between case A and case B is as follows: With case A, when it is necessary to send more information to define a new line, the last predicted point becomes a point of the new line. With case B, two new differences are transmitted, one giving the difference of the first point of the new line from the last predicted point on the old line, and the second difference giving the difference between the second point on the new line and the first point on the new line.

Again the curves of Figures 4 and 5 and entrees of Table 1 show the data compression due to this technique.

First-Order Polynomial Interpolator (FOPI). The FOPI procedure is an extension of the ZOPI technique where first-order polynomials (straight lines) are fitted to as many succeeding data points as possible without exceeding a specified error. When one too many data points is included in the set of successive data points, information sufficient to define a line that fits the previous data points is transmitted. The examined data point becomes the first of a new set of points, and successive data points are added to it until the specified error is exceeded.

To specify the approximating line, the following information is sent:

$$y_{t+n-1} - y_{t+n}$$

$$y_{t+n+1} - y_{t+n}$$

and

N

where these terms have the same meaning as used in the discussion of FOPP. The first piece of information sent defines the starting point of the line, the second its slope, and the third the number of intervals, N, which is equivalent to the length of the line.

Some subleties are involved in achieving optimum results (high compression ratios) with this technique. Because it is desired to transmit as few bits as possible, designating the slope and starting point of the line should require as few bits as possible. This means not all possible slopes are available. Only those exactly described by a few bits should be used, and some optimum coding could be employed to represent those slopes most useful in the approximation. The same is true of the starting point of the line; it must be defined in some discrete way using a minimum number of bits, as a distance from the end point of the previous line. These considerations make the determination of the approximation curves for FOPI quite complex. These restrictions were considered in arriving at the compression ratios for the FOPI results, but the writing of a set of computer instructions to accomplish this was not done because of the complexity.

Although this technique gives high compression ratios as one would expect, the complexity is considerably higher than other schemes.

As can be seen from an examination of the curves of Figures 4 and 5, the interpolator schemes provide more compression than the predictor schemes, but are also more complex to implement. A complexity measure for the FOPI technique would probably be 100 or more. For higher order interpolator procedures, straightforward implementation techniques are not known. Development of such techniques, even if suboptimum, might be a fruitful area for further investigation. The basic difficulty arises because of the minmax error criteria (maximum error should not exceed some specified value) as compared with a mean square error criteria.

Reliability Considerations

When redundancy is removed from transmitted data, an error in the data can cause errors in a large portion of the reconstructed data. To illustrate the seriousness of this effect, consider run length coding where a block of bits A_i is sent describing a function for a given time that is specified in the block of bits. The blocks of A bits describe value and time differences, so that an error in any bit of block A_j causes the data represented by all blocks, A_n, $n > j$ to be in error (conceivably an additional error could cancel out a previous one, but this is unlikely). The effect of such errors can be limited by interspersing among the sequence of A_i blocks, blocks of bits containing absolute data value and timing information. These blocks of bits serve as "checkpoints" and are referred to in this paper as checkpoint bits and designated with the letter Q. With checkpoint bits, an error in a block A_i only causes errors in succeeding blocks until a Q block is encountered. Use of Q bits limits the effect of errors in run length coding, but also decreases the compression as the additional Q bits must be transmitted.

Consider a string of A blocks:

$$A_1\ A_2\ A_3\ A_4\ A_5\ A_6\ A_7\ A_8\ A_9\ \ldots\ A_i\ A_{i+1}\ \ldots$$

Suppose check bits are to be inserted at certain points in the sequence. There are two cases to be considered.

Case I. If insertions are made at regular intervals and the time between intervals is known to the receiver, the Q timing information need only designate that it is a checkpoint and no absolute timing information must be transmitted. Under these conditions, the point at which Q is inserted will probably be in the middle of a run of data, so that information describing the conclusion of the run must be included also. Therefore, for this case, the Q format will have three parts

I = timing or identifying bits

V = absolute data value

F = conclusion of run length.

Thus the preceding string could become:

$$A_1\ A_2\ A_3\ A_4\ Q_1\ A_4^f\ A_5\ A_6^f\ Q_2\ A_6\ A_7\ A_8\ A_9\ \ldots$$

where the A_4^f and A_6^f transmissions correspond to the F portions of Q_1 and Q_2 checkpoints.

Case II. The checkpoints could be inserted only between blocks of code (between A_i and A_{i+1}), but then absolute timing information is required and this could require a large number of bits. In this case the F portion of the Q bits does not need to be transmitted, but the timing information required probably far outweighs this. This case is not considered further.

Error Detection and Correction

Each block of A bits describes two things:

ΔV, the difference in value of the process

m, the number of consecutive time intervals for which the function is the same.

Consider inserting Q bits in a string of A bits at equal time intervals, T (Case I above).

$$Q_0\ A_1\ A_2\ A_3\ Q_1\ A_4\ A_5\ A_6\ A_7\ A_8\ Q_2\ A_9\ A_{10}\ Q_2\ A_9\ A_{10}\ Q_3\ A_{11}\ \ldots$$

$$\longleftarrow T \longrightarrow\longleftarrow T \longrightarrow\longleftarrow T \longrightarrow\longleftarrow$$

Assume only one error occurs in a time interval of 3T. Then the error can be determined to be either in a Q block or in an A block. If the error occurs in a bit in an A block, the error can be isolated to a time interval of length T; and if it occurs in a Q block, the error can be corrected. In some cases, errors in the A blocks of data can be corrected or at least isolated to a few blocks. The proof of these statements can be obtained as follows.

Without loss of generality, consider the foregoing sequence of bits from Q_0 to Q_2 inclusive. Compute the following:

$$\sum_{i=1}^{3} m_i = T, \tag{1}$$

$$\sum_{i=4}^{8} m_i = T \tag{2}$$

$$\sum_{i=1}^{3} \Delta V_i = V_1 - V_0 \tag{3}$$

$$\sum_{i=4}^{8} \Delta V_i = V_2 - V_1 \tag{4}$$

$$\sum_{i=1}^{8} \Delta V_i = V_2 - V_0 \tag{5}$$

If (1) is not satisfied, an error occurred in the timing bits of either blocks A_1, A_2, or A_3 and the error is isolated to an interval of length T. If (2) is not satisfied, an error occurred in the timing bits of either blocks A_4, A_5, A_6, A_7 or A_8. If (5) is satisfied, but not (3) or (4), an error exists in V_1 and can be corrected from (4). Similar checks can be for V_0 and V_2 using sums for V_{-1} to V_1 and V_1 to V_3 respectively. (Assumption is made that not more than one error occurs in any time interval of 3T.) Then if V_0, V_1, and V_2 are correct, and if (3) or (4) is not satisfied, an error exists in one of the appropriate ΔV's. This cannot be further isolated except in some cases. For example, suppose $V_0 = 5$, $V_1 = 11$, $\Delta V_1 = 10$, $\Delta V_2 = -8$, $\Delta V_3 = 5$ and the error is isolated to one of the ΔV's. Let each ΔV have a 5-bit format where the first bit indicates the sign. Each ΔV then has the bit configuration 01010, 11000, and 00101 respectively. Only one of these 15 bits is in error (assumed). Then since

$$\sum_{i=1}^{3} \Delta V_i = 7$$

and since $V_1 - V_0 = 6$ which is correct, the error bit causes the sum to be one too large. A search of the preceding bit patterns for which bit, when changed to its opposite, results in the correct sum, reveals that the only bit satisfying the constraints is the last bit of the third code; that is ΔV_3 should be 4 and have the bit code 00100.

Such isolation is not always possible. For instance, if $V_0 = 5$, $V_1 = 12$, $\Delta V_1 = 10$, $\Delta V_2 = -8$, and $\Delta V_3 = 4$, then $\Delta V_1 + \Delta V_2 + \Delta V_3 = 6$ whereas it should equal 7. The bit patterns for the ΔV's are not 01010, 11000, and 00100. The error is in the last bit of one of these codes because only a change of a bit representing a one will satisfy the equation. Thus, one of the last "0" bits should be a one, but since all of them are zero, no specific isolation can be made.

One possibility that has not been considered is that errors in the I bits can cause Q blocks of bits to appear as A blocks of bits for decoding purposes. Suppose such an error occurs in the Q_1 block. If the Q_1 block has an I code distinct from the Q_0 and Q_2 I codes, then successive receipt of Q_0, Q_2 blocks will indicate that the Q_1 block has not been identified. With this knowledge, Q_1 can be found since sum

$$\sum_{i=1}^{3} m_i = T$$

will not contain an error, and as soon as sufficient m_i's have been summed to equal T, the next block of bits represents the I_1 block of bits. Thus, an error in this block can be corrected. The F portion of the Q block is the same as an A block of bits and really doesn't exist as a separate entity in decoding. An error in the ΔV portion of this F block can be detected, because this ΔV subtracted from the absolute data value of the checkpoint must equal the sum of the ΔV's between the two previous checkpoints. Because these latter two quantities can be checked for errors independent of ΔV, the ΔV of the F portion of the checkpoint block Q can be checked and corrected if in error.

Effect of Checkpoint Bits on Data Compression

Using the preceding scheme of inserting check bits for run length coding, formulas for data compression as a function of reliability can be developed. Reliability is defined here to be the probability that a given data point is received with no error. Other definitions include:

Q = number of checkpoint bits.

E = number of bits per data point for no compression.

N = number of checkpoints per data points.

L = average number of compressed bits/data point with no checkpointing.

B = average number of compressed bits/data point with checkpointing.

$= L + QN$

P_e = probability of error/bit transmitted.

C = compression ratio = number of bits for uncompressed data per data point divided by number of bits for compressed data/data point.

$= \frac{E}{B}$

R = reliability = probability a given data point is received with no error.

P_b = probability that when an error occurs, the error is in the data bits and not the checkpoint bits

$= \frac{L + NM_Q}{L + NQ}$.

P_d = probability that an error occurs in a data bit

$= P_e P_b$.

Using the foregoing definitions, the compression ratio can be written as a function of N as follows:

$$C = \frac{E}{L + QN} \tag{6}$$

The reliability for a given data point is a function of how close the data point is to a previously transmitted checkpoint, because once an error has occurred in a bit, all data points past that bit could be in error. Hence, the probability of a data point being incorrect is higher the more distant it is from a checkpoint. Let M denote the Mth bit from the last checkpoint. The probability that an error has occurred at the Mth bit or before (back to the last checkpoint) is

$$P_M = P_d + (1 - P_d) P_d + P_d (1 - P_d)^2 + \ldots + P_d (1 - P_d)^{M-1}$$

$$= 1 - (1 - P_d)^M$$

Because we are dealing with transmission of compressed data points, the relationship between an error in a transmitted bit and an error in a decoded data point is not as straightforward. It can be stated as follows:

Let

A_i = ith block of compressed data following checkpoint.

r_i = number of bits for compressed data block A_i.

s_i = number of data points compressed into block A_i.

P_i = probability error is in ith data point following checkpoint (an error in a previous data point - back to the checkpoint - results in an error in this point as well).

Then

$$P_i = P_d + (1 - P_d) P_d + (1 - P_d)^2 P_d + \ldots$$

$$+ (1 - P_d)^{r_1 - 1} P_d = 1 - (1 - P_d)^{r_1}$$

$$P_1 = P_2 = P_3 = \ldots = P_{s1}$$

$$P_{s1+1} = (1 - P_1) \left[P_d + (1 - P_d) P_d + \ldots (1 - P_d)^{r_2 - 1} P_d \right] + P_1$$

$$= 1 - (1 - P_d)^{r_1 + r_2}$$

$$P_{s1+1} = P_{s1+2} = P_{s1+3} = \ldots P_{s1+s2}$$

and in general

$$P_{k+1} = 1 - (1 - P_d)^q$$

$$P_{k+1} = P_{k+2} = P_{k+3} = \ldots P_{k+s_i}$$

where

$$k = \sum_{j=1}^{A_{i-1}} s_j, \quad q = \sum_{j=1}^{A_i} r_j$$

For run length coding s_i is essentially a random variable, and for Huffman coding, r_i is also random. Let

$$r = E(r_i)$$

$$s = E(s_i)$$

then

$$P_n \quad 1 - (1 - P_d)^{nr/s}$$

and

$$R = 1 - P_n \approx (1 - P_d)^{nr/s}$$

$$= \left[1 - \frac{P_e(L + NM_Q)}{L + N(Q - M_Q)} \right]^{nr/s} \qquad n < N^{-1} \tag{7}$$

When an error does occur, and assuming it cannot be isolated or corrected as previously discussed, the number of data points in error is

$$G = N^{-1} \tag{8}$$

Equations 6, 7, and 8 are plotted in Figure 4 for the Mariner 4 data with a ZOPP compression procedure. As can be seen from these curves, an increase in N results in fewer data points in error per bit error, and increases very slightly the reliability figure, but decreases the compression ratio. Such relationships are necessary in the design of a data compression system, because without checkpoint bits (N = 0) all data points could possibly be in error for a single bit error.

Conclusions and Comments

Data compression techniques applied to sensor data gathered during space missions often permits a several-fold increase in the amount of data that can be transmitted using the same telemetry equipment, or for a constant raw data input, permits reduction in telemetry equipment. Several simple, but effective and reliable procedures have been developed, and this paper has indicated some of the tradeoffs that exist in selecting a procedure. An example set of raw data from the Mariner 4 mission was used for these comparisons, and it was shown that an error-free compression ratio of more than 3:1 is possible for this piece of data.

An important consideration in a data compression system is the effect an error in a transmitted bit will have on the decoded data. Because one of the aims of any compression scheme is the removal of redundant information, a bit error often results in errors in several received data points. Some means for limiting the effect of such errors were presented and discussed, particularly as to their effect on the data compression ratio.

Attempts to apply data compression to space activities should be pursued, because it has been pointed out that the data received from spacecraft is increasing at a "terrifying rate."[72] In the 1960-61 period, there were 13 satellites with bandwidths to 100 kc, for a total of about 26×10^9 data points. In the next two-year period, 1962-63, 37 satellites were launched or planned for with telemetry data bandwidths to 300 kc and with TV tape channels to 3.5 Mc, for a total of about 18×10^{11} data points. Even more data have been obtained and can be expected in later periods as the space program expands.

Table 1. Results of Compression Analysis, Using a Variety of Techniques

TECHNIQUE	# BITS	COMPRESSION RATIO	COMPLEXITY MEASURE	MAXIMUM APPROXIMATION ERROR* (%)
1. Direct Coding	1320	1	2	0
2. Difference Coding	660	2.0	5	0
Entropy of Code	319	4.14		0
3. Huffman Code (Optimal Coding)	341	3.88	8	0
4. ZOPP, A=0	435	3.04	12.6	0
ZOPP, A=1	150	8.80	11.5	2.56
ZOPP, A=2	105	12.6	11.3	5.12
ZOPP, A=3	77	17.2	11.2	7.68
ZOPP, A=4	63	20.9	11.2	10.24
ZOPP, A=5	56	23.6	11.1	12.80
ZOPP, A=6	48	27.4	11.1	15.36
5. ZOPI, A=0	435	3.04	16.1	0
ZOPI, A=1	152	8.70	14.1	2.56
ZOPI, A=2	81	16.3	13.5	5.12
ZOPI, A=3	63	21.0	13.4	7.68
ZOPI, A=4	45	29.3	13.3	10.24
ZOPI, A=5	40	33.0	13.2	12.80
ZOPI, A=6	40	33.0	13.2	15.36
6. FOPP$_A$, A=0	528	2.50	17.2	0
Uses only one new transmitted point when an error occurs — A=1	389	3.39	16.7	2.56
A=2	329	4.01	15.9	5.12
A=3	413	3.20	16.0	7.68
A=4	447	2.95	16.3	10.24
FOPP$_B$, A=0	640	2.06	14.6	0
Send two data points when error occurs — A=1	320	4.12	16.2	2.56
A=2	189	6.97	16.3	5.12
A=3	150	8.79	16.5	7.68
A=4	90	14.7	16.7	10.24
A=5	110	12.0	16.7	12.80
A=6	80	16.5	16.8	15.36

Table 1. (Cont)

TECHNIQUE	# BITS	COMPRESSION RATIO	COMPLEXITY MEASURE	MAXIMUM APPROXIMATION ERROR* (%)
7. FOPI, A=0	435	3.04	Not Computed Estimated to be of order of 100-500.	0
FOPI, A=1	104	12.7		2.56
FOPI, A=2	52	25.4		5.12
FOPI, A=3	30	44.0		7.68
FOPI, A=4	28	47.0		10.24
FOPI, A=5	14	94.2		12.80
FOPI, A=6	14	94.2		15.36

*Error as a % of maximum difference in signal = 23.

Table 2. Statistics and a Huffman Code for Differences of Example

Difference	Probability of Occurrence	Code
0	0.645	0
+1	0.234	10
-1	0.107	110
+2	0.023	1110
-2	0.005	1111

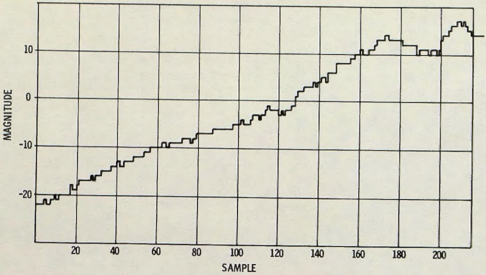

Figure 1. Example Data Set - Mariner 4 Magnetometer Readings (Y Axis), Time 201433 - 202631, Day 333 1965

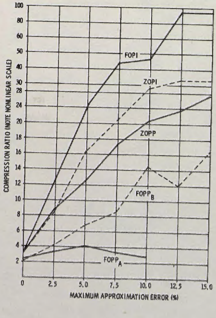

Figure 2. Approximation Error vs Compression Ratio

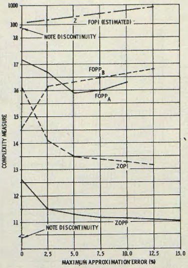

Figure 3. Complexity Measure vs Approximation Error

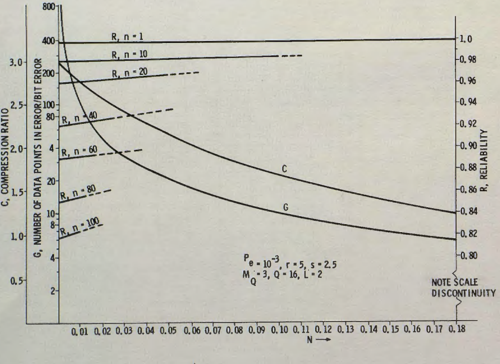

Figure 4. Compression Ratio, Reliability, and Error Effect Curves for $P_e = 10^{-3}$

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